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Aircraft Fires, Smoke Toxicity, and Survival: An Overview

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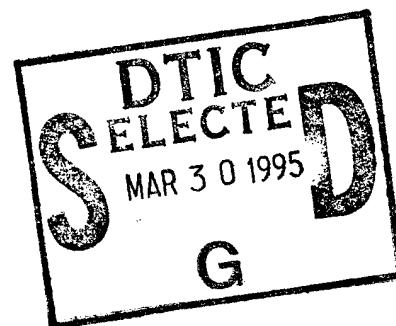
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16. Abstract <p>In-flight fires in modern aircraft are rare, but post-crash fires do occur. Cabin occupants frequently survive initial forces of such crashes but are incapacitated from smoke inhalation. According to an international study, there were 95 fire-related civil passenger aircraft accidents world-wide over a 26-year period, claiming \approx2400 lives. Between 1985-1991, about 16% (32) of all US transport aircraft accidents involved fire and 22% (140) of the deaths in these accidents resulted from fire/smoke toxicity. Our laboratory database (1967-1993) indicates that 360 individuals in 134 fatal fire-related civil aircraft (air carrier and general aviation) accidents had carboxyhemoglobin saturation levels, with or without cyanide in blood, high enough to impair performance. Combustion toxicology is now moving from a descriptive to a mechanistic phase. Methods for gas analyses have been developed and combustion/animal-exposure assemblies have been constructed. Material/fire-retardant toxicity and interactions between smoke gases are being studied. Relationships between gas exposure concentrations, blood levels, and incapacitation onset are being established in animal models. Continuing basic research in smoke toxicity will be necessary to understand its complexities, and thus enhance aviation safety and fire survival chances.</p>			
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AIRCRAFT FIRES, SMOKE TOXICITY, AND SURVIVAL: AN OVERVIEW

AIRCRAFT FIRES

Since primitive times, fire has been an integral part of mankind's day-to-day life and efforts to control fire and use it for constructive purposes remain a continuous process. In spite of this, fire continues to be linked with loss of lives and property, and the advent of the mechanical age has altered, but not eliminated catastrophic fires. Uncontrolled fires threaten homes, factories, and transportation systems, including air travel.

Modern aircraft benefit from continuing research in fire retardant materials and improved fire extinguishing systems to such an extent that in-flight fires are rare occurrences. However, survivable crashes followed by fire occur, primarily from fuel spills around the downed aircraft. Although cabin occupants may survive the initial forces of such crashes, they are frequently unable to escape from the fire environment because of performance impairment from smoke-caused toxicity and visual obscuration. Postcrash fire is considered to be the most important determinant of pilot fatalities in commuter aircraft/air taxi crashes (Li and Baker, 1993).

According to a study by the International Cabin Water Spray Research Management Group (ICWSRMG), there were 95 fire-related civil passenger aircraft accidents world-wide over a 26-year period (ICWSRMG, 1993). Fire claimed approximately 2400 lives in those accidents. A US General Accounting Office (GAO) publication reveals that approximately 16% (32) of all US transport aircraft accidents between 1985 and 1991 involved fire and 22% (140) of the fatalities in these accidents resulted from the effects of fire and smoke (GAO, 1993). During 1967-1993, the Federal Aviation Administration's (FAA's) Civil Aeromedical Institute (CAMI) analyzed post-mortem samples from 134 US fire-related civil aircraft (air carrier and general aviation) accidents;

analyses revealed that 360 victims from these accidents had blood carboxyhemoglobin saturation levels, with or without cyanide in blood, high enough to impair their abilities to evacuate the aircraft (CAMI, 1994).

FIRE COMPLEXITY

Fire is a complex, dynamic, physicochemical phenomenon. It is a result of a rapidly developing chemical reaction that generates smoke, heat, flame, and light. Each fire is different. Smoke, its prominent and integral component, is a mixture of various gases, liquids, and solids in colloidal solution. In other words, smoke is a complex of particulate matter, vapors, and gases suspended in the fire atmosphere. It may be light, dark, thick, or thin, and may diminish the transmission of light and obscure vision.

Types and amounts of combustion products generated depend upon the chemistry of the materials involved and the environmental conditions present during a particular fire (Gad, 1990). Burning conditions and rates of fire progression further play contributory roles in combustion product generation. Smoke composition and toxicity can change drastically when different materials are present in a combustion environment and can be further altered by the presence of fire retardants and pigments. A material burned under one condition could be practically nontoxic, but could be very toxic when burned under a different condition (Gad, 1990; Crane et al., 1986). For example, cotton produces large quantities of carbon monoxide when burned under low-oxygen, smoldering conditions, but the much less toxic carbon dioxide dominates under flaming conditions; Nylons tend to break down into their relatively nontoxic monomers at low temperatures, but produce toxic hydrogen cyanide gas when flaming. Fire retardants

decrease flammability, but they may also enhance smoke toxicity (Petajan et al., 1975). Most cabin furnishings contain carbon, and will produce carbon monoxide when burned. Silk, wool, and many nitrogen-containing synthetics are common sources of hydrogen cyanide in fires (Gad, 1990). Irritants, such as hydrogen chloride and acrolein, can be produced from burning wiring insulation and some other cabin materials (Gad, 1990; Crane et al., 1979). Generally, carbon monoxide levels increase as oxygen concentrations decrease during fires.

SMOKE TOXICITY

Besides visual obscuration, smoke components produce adverse biological effects of reversible or irreversible nature. Carbon monoxide and hydrogen cyanide produce acute effects, causing incapacitation and, subsequently, death. Since these gases are generally present in substantial amounts in smoke, a potential exists for simultaneous exposures, with the resulting combined effects on biological systems. Inhalation of less-than-lethal amounts of these gases can cause dizziness, confusion, and physical incapacitation. Irritants can induce tears, pain, and disorientation; other reactive molecules in smoke can produce delayed toxicological/pathological effects (Gad, 1990).

The toxicity mechanisms for some combustion gases have been elucidated. Carbon monoxide combines with the hemoglobin in blood and, thus, interferes with oxygen transport, while hydrogen cyanide inhibits oxygen utilization at the cellular level (Gossel and Bricker, 1994; Smith, 1986). The simultaneous exposure to both gases produces a combined effect of severe hypoxia. Carbon dioxide, an otherwise relatively innocuous fire gas, increases the respiratory rate, resulting in an increase in uptake of the more toxic gases. Finally, the decreased oxygen level found in most fire scenarios further diminishes the availability of oxygen for utilization at various biological sites.

FIRE RESEARCH

Although fire research is being conducted throughout the world in many government sectors, industries, research institutions, and universities, the FAA emphasizes research directly related to fire safety in aviation. The FAA Technical Center in Atlantic City specializes in the engineering components, while the FAA CAMI programs in Oklahoma City focus on medical aspects of cabin fire research. During the last 2 decades, the CAMI programs have been playing significant contributory roles in combustion toxicology.

CAMI's combustion toxicology research was initiated in 1970, when a Capitol International Airways DC-8 crashed on takeoff at Anchorage, Alaska, and blood specimens from the victims were found to contain cyanide inhaled during the post-crash fire (NTSB, 1972). The FAA, as well as the public, wanted to know the source of the cyanide and what could be done to prevent a recurrence of cyanide exposures. At that time, little was known about the potential for aircraft interior materials to produce toxic combustion gases. Even more surprising was the lack of documented data on the toxicity of individual combustion gases. During the ensuing years, scientists at the Technical Center and CAMI have continued systematic research to answer some of these important questions.

Initial CAMI research activities were directed toward answering some basic questions related to smoke toxicity. Some questions were: "What gases are produced from each material? What are the effects of different pyrolysis conditions on the kind and quantity of gases produced? What biological end-point is best related to escape time in a fire environment?" Perhaps the most critical question was, "How do we address the cumulative effects of fire gas mixtures, since real fires seldom produce only a single toxic gas component in smoke?"

CAMI scientists designed and developed combustion assemblies and animal exposure chambers (Crane et al., 1989; Sanders et al., 1986; 1993). These systems permitted the analyses of combustion gases, individually and in combinations, as well as in smoke generated under a variety of conditions. The net effects of gas/smoke exposure were determined using the laboratory rat. Time-to-physical-incapacitation was selected as a measure of the toxic gas effect related to escape time in a fire—incapacitation occurs much earlier than death and effectively signals the end of the individual's escape efforts (Crane et al., 1977; Sanders et al., 1992). By relating the cumulative gas concentration-exposure time required to produce incapacitation, equations were developed that permitted the prediction of escape time in known concentrations of combustion gases. This approach also allowed the inclusion of smoke toxicity considerations in fire modeling development. These studies were extended to the mixtures of carbon monoxide-hydrogen cyanide (Crane et al., 1989; Sanders et al., 1994) and of carbon monoxide-acrolein (Crane et al., 1992).

In cooperation with the FAA Technical Center scientists, the CAMI scientists ranked 75 cabin interior materials for toxicity of their combustion products, using time-to-incapacitation (in the rat) as the measured effect (Crane et al., 1977; Spurgeon et al., 1977). The bioassay produced very precise and reproducible incapacitation times for each material, when burned under identical conditions. Further studies also showed that changes in the pyrolytic conditions caused marked changes in time-to-incapacitation and, thus, in the relative toxic ranking of materials. Additional studies involving aircraft panels (Crane et al., 1986), seat fire-blocking materials (Sanders et al., 1986), and wiring insulations (Crane et al., 1979) further defined the changes in toxic gas output, and the corresponding biological responses, when identical materials were tested under different pyrolytic conditions.

CAMI combustion toxicology research findings have been published as US Government Office of Aviation Medicine technical reports, as research papers in the leading journals, and have been presented

at scientific meetings. These findings can be summarized as: (i) development of two unique combustion assemblies and animal exposure chambers for combustion toxicology tests; (ii) toxicity rankings of over 100 aircraft cabin materials on the bases of lethality and incapacitation; (iii) elucidation of the interaction between a toxic gas and an irritant; (iv) characterization of effects of elevated temperature on carbon monoxide-caused incapacitation in rats; and (v) establishment of relationships between exposure concentration of carbon monoxide and/or hydrogen cyanide, time-to-incapacitation (exposure time), carboxyhemoglobin, and blood cyanide parameters. The information from the above research has application in the interpretation of postmortem forensic toxicological findings and reconstruction of aircraft accidents, and could be utilized in developing more effective protective breathing devices.

ISSUES AND DIRECTIONS

Current industrial research deals primarily with the flammability of materials and the concurrent development and use of more efficient fire retardants—this is a practical response to a real problem. If cabin materials do not burn, the only toxicological threat is from the gases produced by burning fuel; however, they do burn when ignited by fuel-fed, post-crash fires. Therefore, the resulting toxicological problems cannot be ignored.

One frequently discussed and genuine issue is whether there is a need for a "standard" test for smoke toxicity. Why are aircraft cabin interior materials not regulated based on their potential fire toxicity? Since cabin materials are regulated on the basis of flammability, the question is a logical one. The answer, in its simplest form, is that there is no standard fire. Burning conditions could drastically alter the smoke composition and, thus, the toxicity of the material—examples are cotton and Nylons. No single test condition would allow the relative potential toxicity ranking of all materials based on their probable performance in an actual fire. Despite the need to select the least hazardous material types, the development of a "standard" test must be approached with extreme caution.

Such a method must be based on firm scientific principles and must remain unbiased in its application. Validation of such a small-scale test will require parallel experiments with large-scale fires to compare the results of defined loads of test materials. Depending upon projected progress in fire science and technology, final development of an acceptable, scientifically valid test may be several years in the future.

So, what research directions are most likely to further enhance the chances for fire survival? Currently used fire-blocking layers now improve the fire resistance of polyurethane seat cushions in aircraft, and proposed cabin water spray systems exhibit considerable potential for slowing the spread of cabin fires. These water spray systems have also proved valuable for scrubbing water soluble fire gases, such as hydrogen cyanide and hydrogen chloride, from smoke atmospheres. New cabin materials can now be more realistically selected, taking into consideration those fire related properties that can be measured, such as ignition temperatures and heat release rates.

Future fire modeling programs will require increasingly precise mathematical data on material behavior and toxic gas production, if they are to be of value in predicting potentially hazardous situations. Relationships between laboratory- and large-scale material combustion tests must be established before small scale tests can be used to estimate new material behavior in a real fire. The toxic contributions of fire generated aerosols, the visible components of smoke, are not well understood and their contribution to overall smoke toxicity needs to be evaluated. Fire retardants must be carefully examined, since some enhance smoke toxicity when heated above the fire-retarded material's ignition temperature. In the biomedical area, specific toxicity mechanisms for individual combustion gases and multiple gas interactions need further exploration. Blood levels of these gases should be correlated with exposure concentration and duration, using suitable toxicological endpoints related to escape time. Causal relationships between combustion gas blood levels and human physiological impairment should be established to

assist medical accident investigators in interpreting postmortem forensic findings. The comparative toxicology of those newer, environmentally safe HALON substitutes proposed for use inside aircraft cabins should be carefully studied.

Continuing fundamental research in smoke toxicity, fire safety, and fire hazard assessment in aircraft accidents is clearly warranted. As fire science changes from a descriptive discipline to a mechanistic one, multidisciplinary skills will be required to develop practical applications from existing and projected research. Such collective, global cooperation will be necessary for understanding the complexities of smoke toxicity. These efforts can be promoted through national and international colloquia dealing with fundamental advances in combustion toxicology; meetings like these will open avenues for new research and will provide informed guidance toward the development of a scientifically valid smoke toxicity test standard for materials. Continuing cooperative research efforts between engineering and biomedical scientists will greatly increase the chances for fire survival.

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